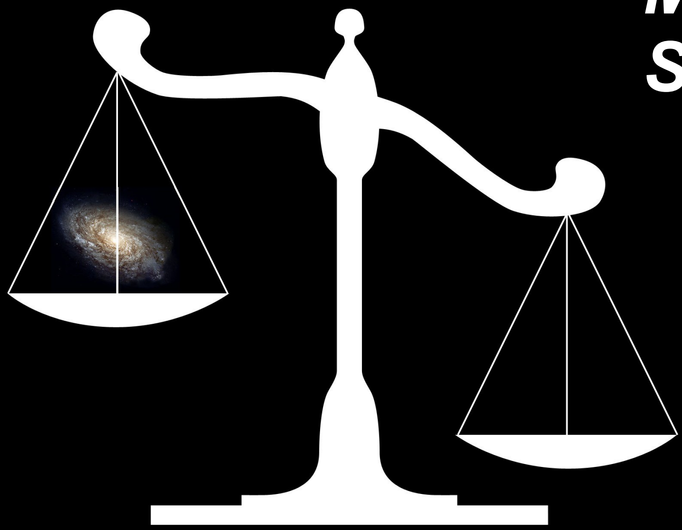
Astrophysical Constraints on Direct Detection:

Multi-Component Dark Matter Scattering and Stability



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[ArXiv:1308.xxxx]

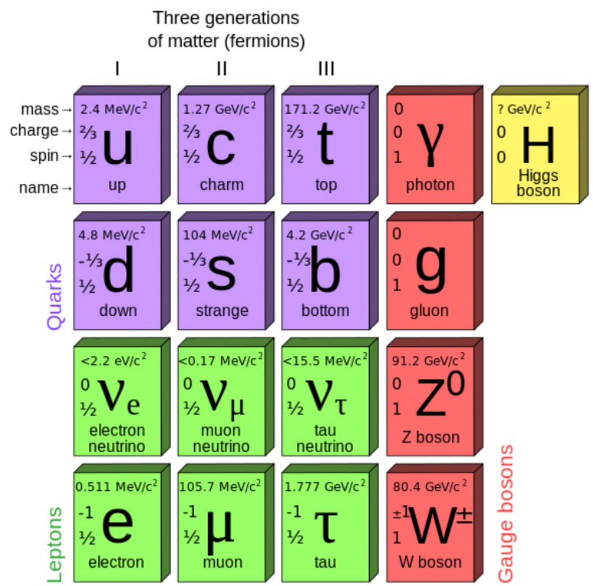
In collaboration with Keith Dienes (UofA), Jason Kumar (UH), and Brooks Thomas (UH).

DPF2013 – UC Santa Cruz

Why Consider Multi-Component Dark Matter?

Given that one accepts the hypothesis of dark matter, there are two scenarios...

SCENARIO I



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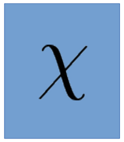

*Everything we **currently** know of... ~20% of the matter in the universe.*

*A **single** extra particle, making up the remaining 80%.*

...OR

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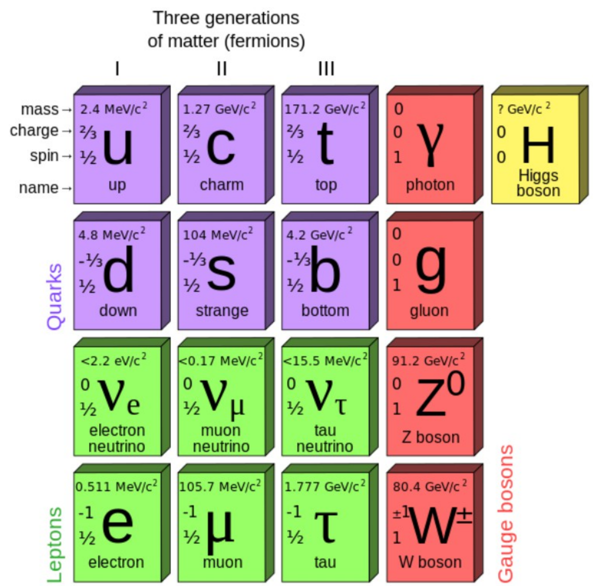
SCENARIO II



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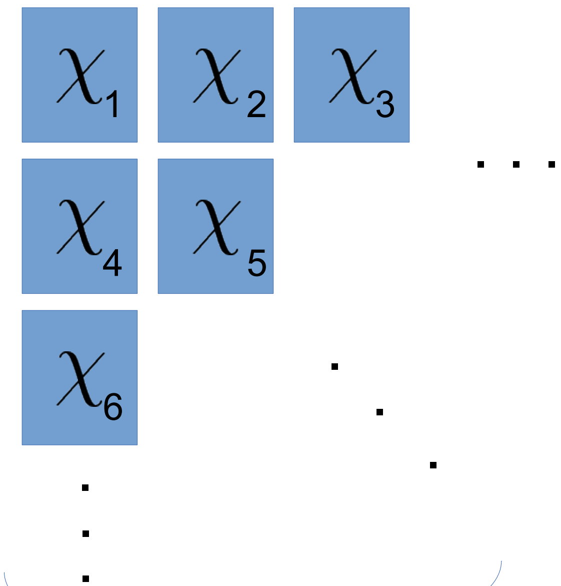

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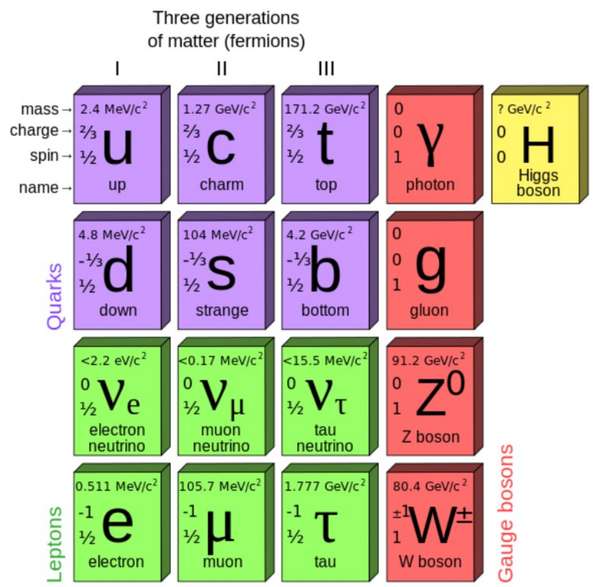

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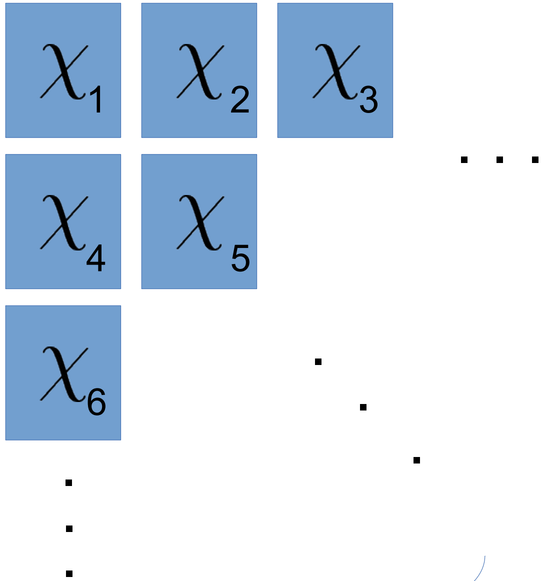

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*A **dark sector**, consisting of many different particles which make up the remaining 80%.*

*Given how complicated the standard model is, it is **worth considering** the possibility that the dark sector is complicated as well!*

Ok, but what are some more concrete reasons to motivate models of multi-component DM?

- **DAMA/CoGeNT/CRESST/etc. VS XENON100/COUPP/etc.**
  Reconciling these sets of experiments difficult in vanilla DM models
  - -Inelastic Dark Matter (Smith & Weiner, 2001)
  - -Mirror Matter (Foot, 2004)
  - -Exothermic Dark Matter (Graham, Harnik, et. al., 2010)

- **Positron excess – Pamela, FERMI, AMS-II**
  Similar excess not observed in antiprotons
  Excess too big for thermal freezeout production
  - -Multiple DM particles (Zurek et. al., 2008; Feldman, et. al., 2010)

- **Gamma ray line at 130 GeV (FERMI)** *(...or just "earth limb" photons?)*
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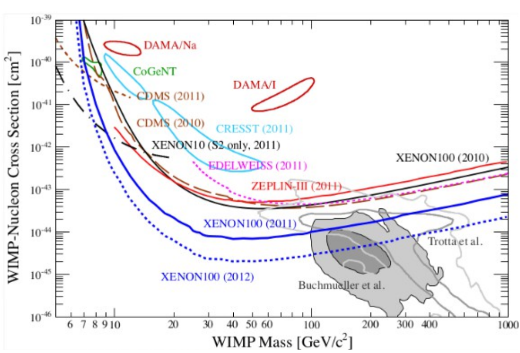

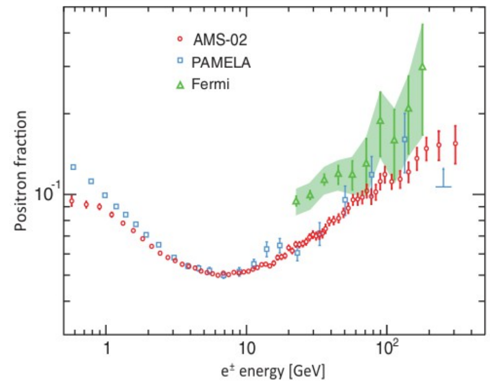

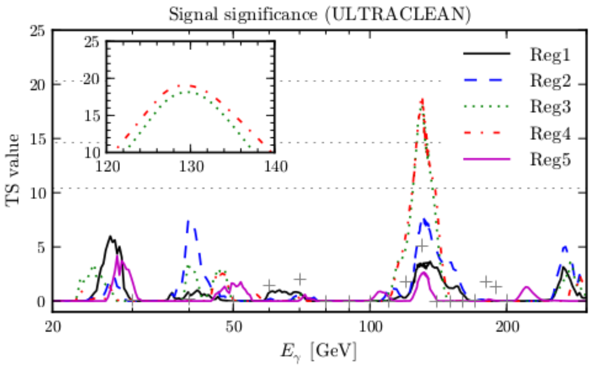

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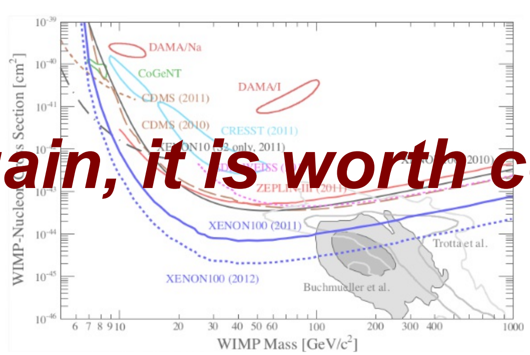
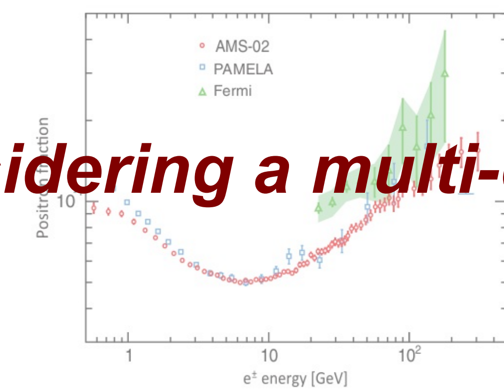
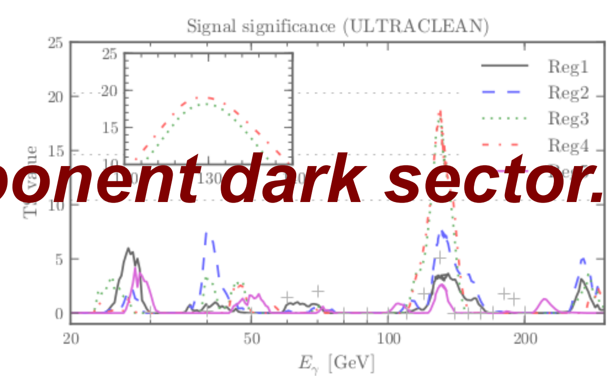


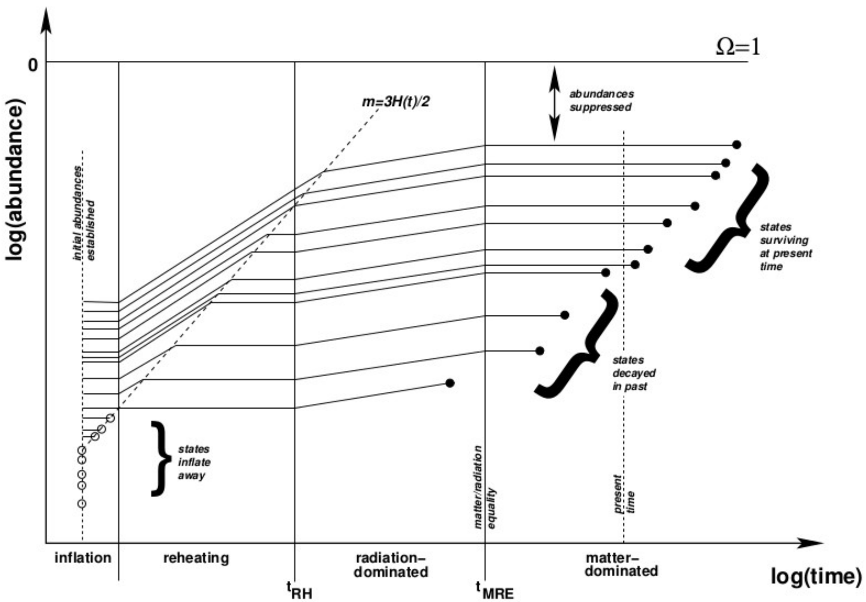


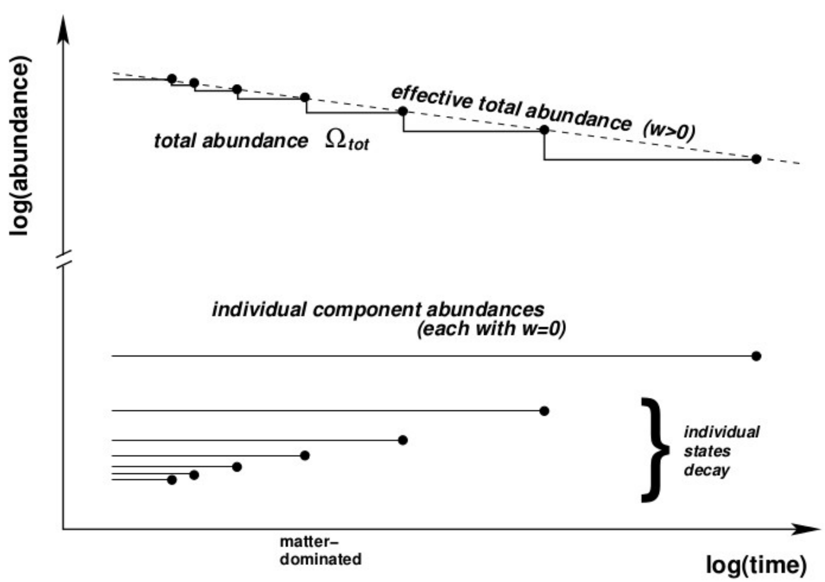


Again, it is worth considering a multi-component dark sector.

Dynamical Dark Matter (DDM)
(Dienes & Thomas, 2011)

$$\Omega_{\text{tot}} \equiv \sum_i \Omega_i$$

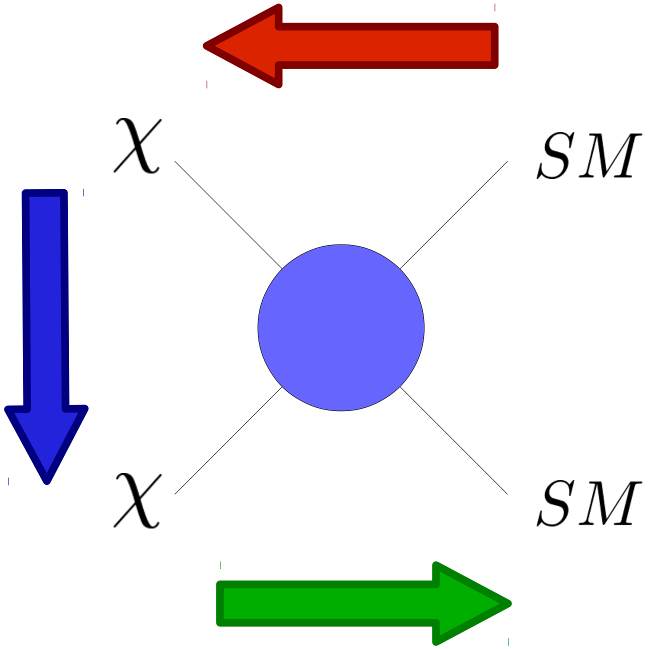




- Dark matter can be an *ensemble* of different (semi-stable) states, each with their own abundances, masses, lifetimes.
- Total DM abundance can change in time.
- Single component *vanilla* DM is **a limiting case of DDM.**
- Viable models exist (e.g., Kaluza-Klein axions) which exhibit the unique phenomenology of DDM.
- **Dark matter is not necessarily stable.** Rather, there exists a *balance between lifetimes and abundances.*

DDM is a nice framework for discussing multi-component dark matter, and ***opens up a new window*** *into dark matter physics...*

Our non-gravitational windows into dark matter...



- **DM-SM scattering** – (direct detection)
- **DM annihilation to SM** – (indirect detection)
- **Collider Production**

Same diagram $\Longrightarrow$ Processes related by "crossing symmetry"

If there are two or more species of dark matter, we also have...

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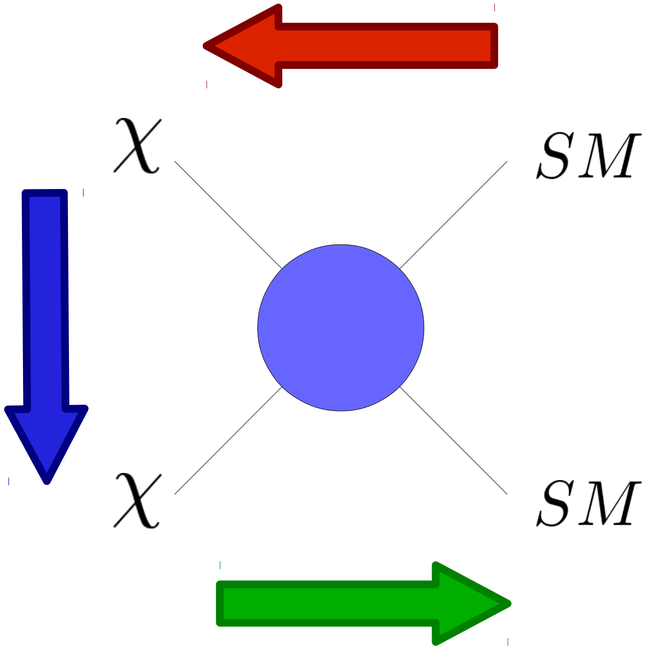

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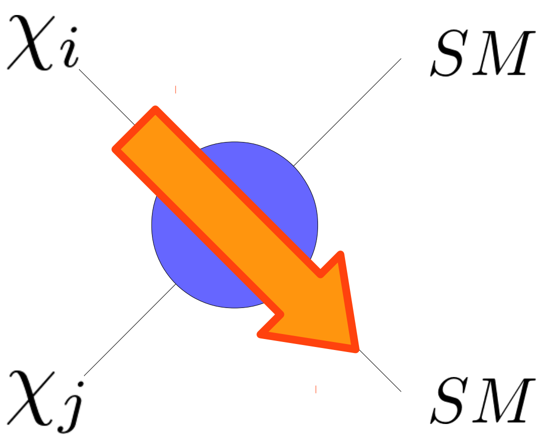
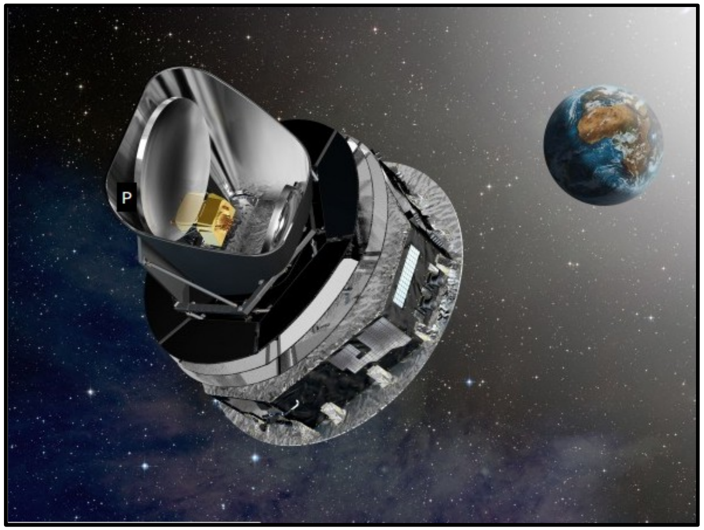


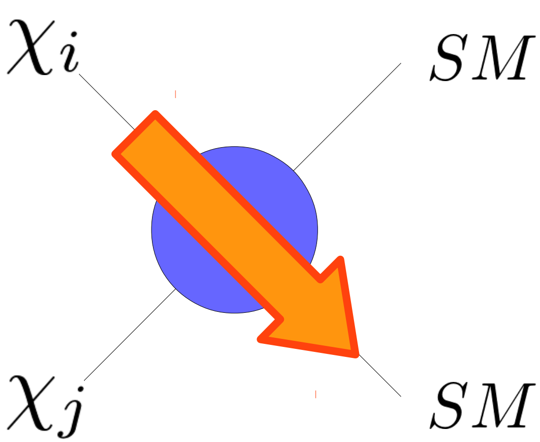
- **DM decay to DM+SM** – (indirect detection!)

Again, same diagram $\Longrightarrow$ Decay rate **also** correlated with the above cross sections!

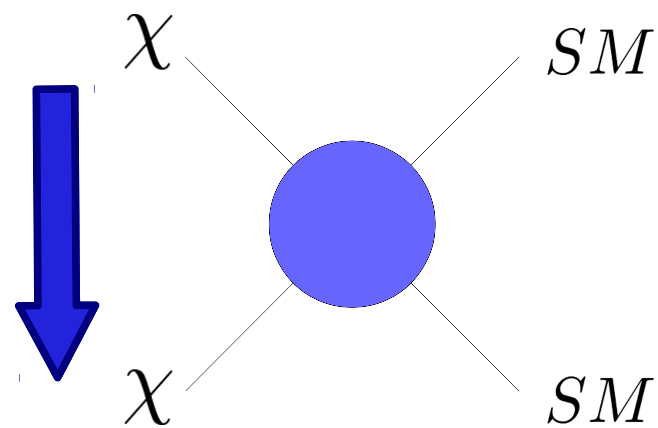
We now have a new relationship at our disposal...

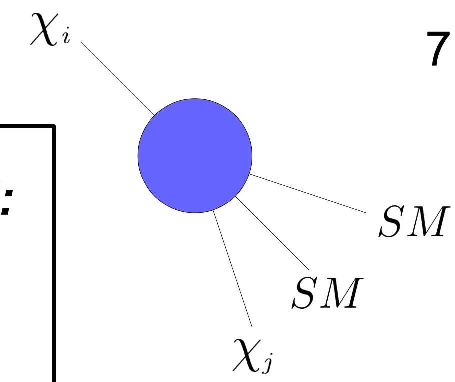
The Final Frontier...





Dante's Inner Circles...





To see how this works, we study an illustrative and general model:

- Two fermionic DM particles, χ_i and χ_j
- Mass difference of order $\Delta m_{ij} \equiv m_j - m_i \lesssim \mathcal{O}(100 \text{ keV})$
  (Thus these operators are relevant for direct detection)
- Effective contact couplings between DM particles and quarks:

$$\mathcal{L}_{\text{int}}^{(\text{fund})} = \sum_{\alpha} \sum_{ijff'} \frac{c^{\alpha}_{ijff'}}{\Lambda^2} \mathcal{O}^{(\alpha)}_{ijff'}$$

$$\mathcal{O}^{(S)}_{ijff'} = (\overline{\chi}_i \chi_j)(\overline{q}_f q_{f'})$$
$$\mathcal{O}^{(P)}_{ijff'} = (\overline{\chi}_i \gamma^5 \chi_j)(\overline{q}_f \gamma^5 q_{f'})$$
$$\mathcal{O}^{(V)}_{ijff'} = (\overline{\chi}_i \gamma^\mu \chi_j)(\overline{q}_f \gamma_\mu q_{f'})$$
$$\mathcal{O}^{(A)}_{ijff'} = (\overline{\chi}_i \gamma^\mu \gamma^5 \chi_j)(\overline{q}_f \gamma_\mu \gamma^5 q_{f'})$$
$$\mathcal{O}^{(T)}_{ijff'} = (\overline{\chi}_i \sigma^{\mu\nu} \chi_j)(\overline{q}_f \sigma_{\mu\nu} q_{f'})$$

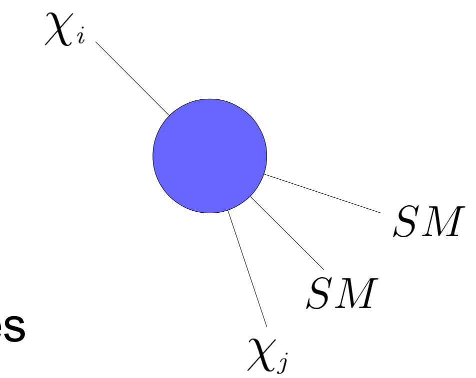
- χ_is uncharged
- Generation independent
- $\Delta m \lesssim \mathcal{O}(100 \text{ kev}) \Rightarrow$ Only light quarks contribute to decay.

$$c^{(\alpha)}_{ijff'} = \begin{pmatrix} c^{(\alpha)}_{iju} & 0 & 0 \\ 0 & c^{(\alpha)}_{ijd} & 0 \\ 0 & 0 & c^{(\alpha)}_{ijd} \end{pmatrix}$$

In what follows we choose to express results in terms of the coefficients

$$c^{(\alpha)}_{\pm} = c^{(\alpha)}_u \pm c^{(\alpha)}_d$$

Decay Channels



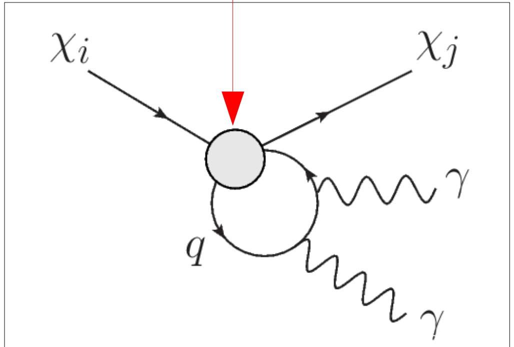
- Since $\Delta m_{ij} \lesssim \mathcal{O}(100\ \mathrm{keV})$, only possible SM decay products are low energy **photons** and **neutrinos**
- χ_i only couples to quarks, which at these low energies are bound as mesons

$\Longrightarrow$ Decay of χ_i proceeds through off-shell (loops of) mesons

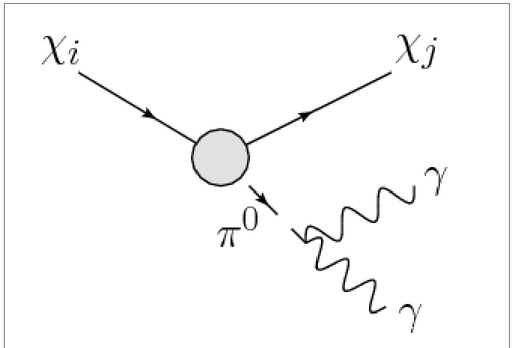
$\Rightarrow$ Decay widths highly suppressed

We have this coefficient...

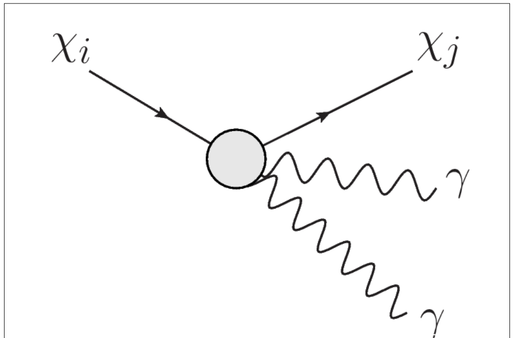
...but how do we get here?



Microscopic Theory



Low Energy EFT



Effective χ-γ couplings

$$\mathcal{L}_{\mathrm{int}}^{(\mathrm{fund})} \ni \frac{c_{\pm}^{(p)}}{\Lambda^2}(\overline{\chi}_j\gamma^5\chi_i)(\overline{q}\gamma^5 q)$$

Chiral Perturbation Theory

$$\mathcal{L}_{\mathrm{int}}^{(\mathrm{eff})} \ni \frac{C_P}{\Lambda^2}(\overline{\chi}_j\gamma^5\chi_i)F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Decay Widths

We now have the entire effective Lagrangian for the interactions $\chi_j \to \chi_k \gamma$ and $\chi_j \to \chi_k \gamma\gamma$, in terms of our original high energy coefficients:

$$\mathcal{L}_{\rm eff} = \frac{c_S}{f\Lambda^2}(\overline{\chi}\chi)F_{\mu\nu}F^{\mu\nu} + \frac{c_P}{f\Lambda^2}i(\overline{\chi}\gamma^5\chi)F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{c_V}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial^\nu F_{\mu\nu} + \frac{c_{V'}}{f^2\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial_\rho\partial^\rho\partial^\nu F_{\mu\nu} + \cdots$$

...from whence we compute the decay widths. Things are NOT PRETTY, but simplify considerably with the approximation $\Delta m \ll \{m_j, m_k\}$:

$$\Gamma_S^{(\gamma)} \approx \frac{2c_S^2\Delta m^7}{105\pi^3 f^2\Lambda^4}$$

$$\Gamma_P^{(\gamma)} \approx \frac{2c_P^2\Delta m^9}{315\pi^3 f^2\Lambda^4 m_j^2}$$

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$$\Gamma_{PA}^{(\gamma)} \approx \frac{2c_P c_A\Delta m^9}{315\pi^3 f^3\Lambda^4 m_j}$$

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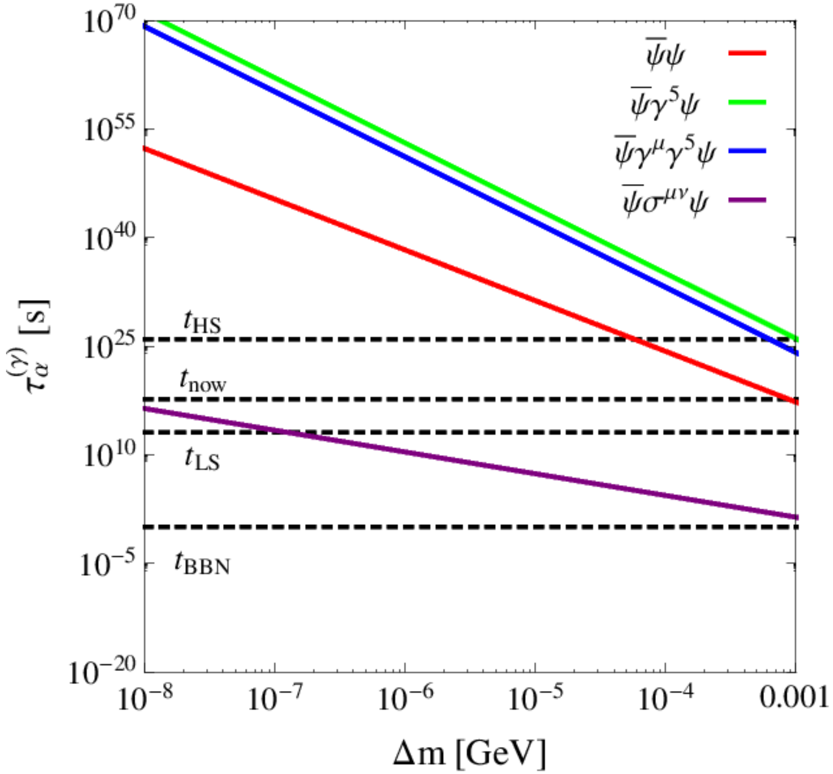

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$$\Lambda = 10 \text{ TeV}$$

$$m_i = 100 \text{ GeV}$$

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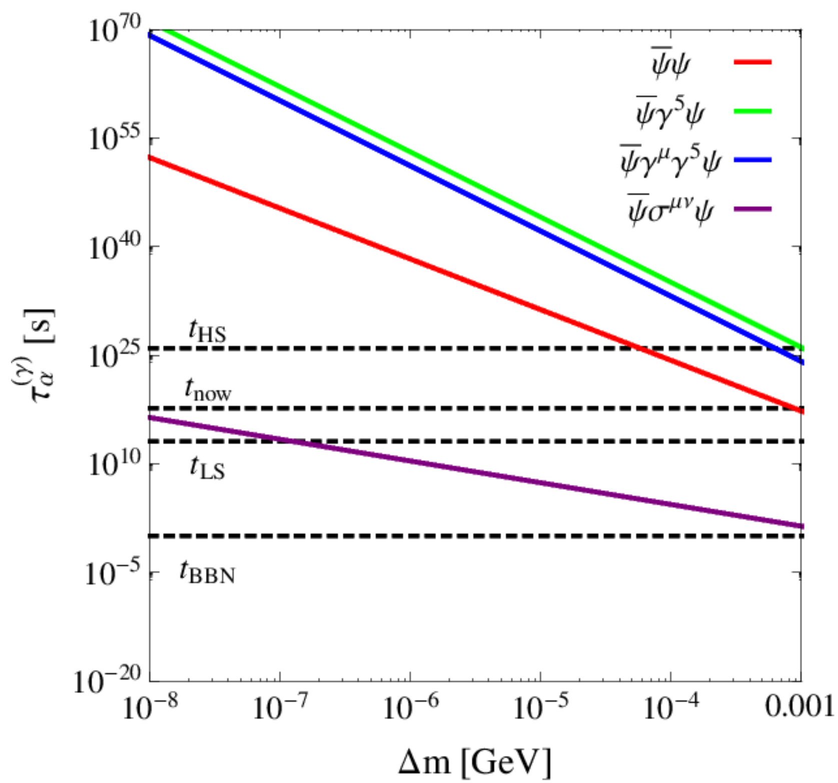

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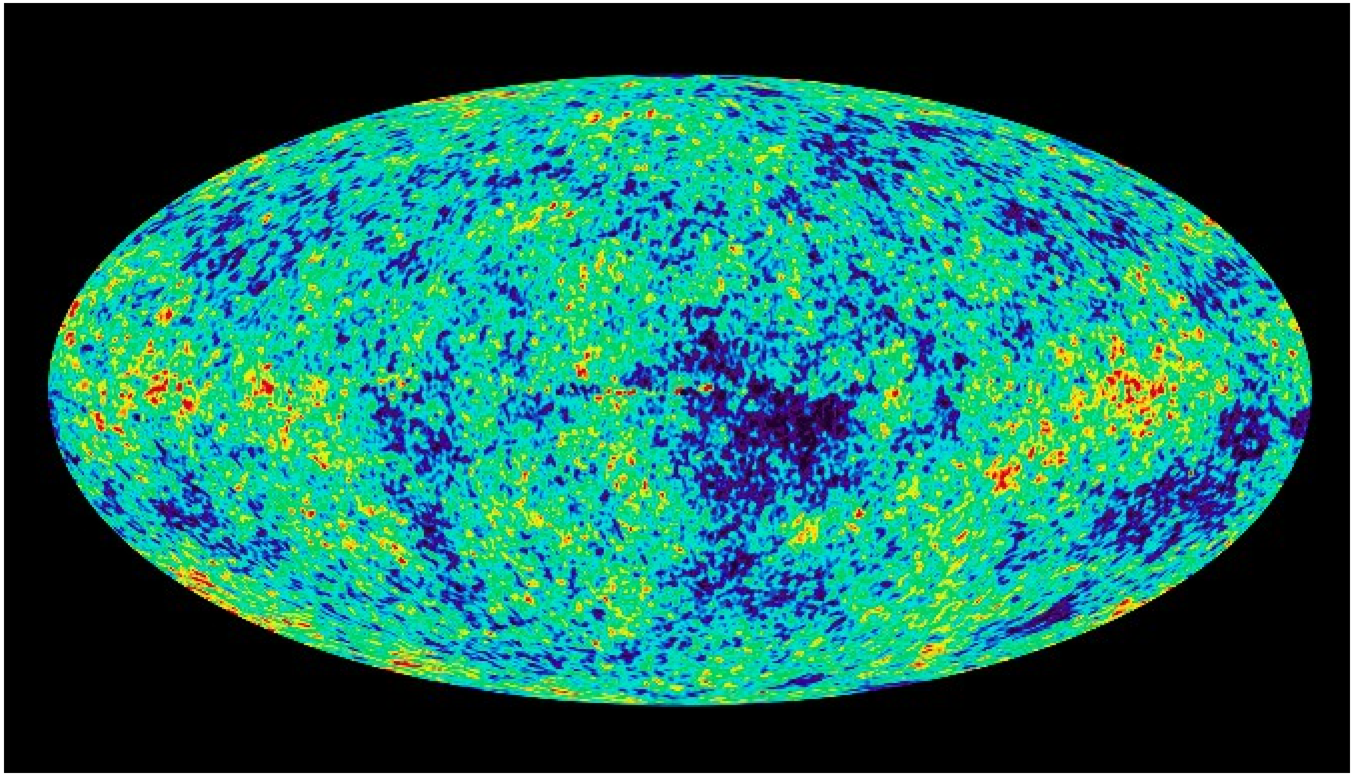
$$\Lambda = 10 \text{ TeV}$$

$$m_i = 100 \text{ GeV}$$

We can clearly achieve models where the heavier DM component remains undecayed to this day

Decay Widths

This is good, since there are tight constraints from the CMB on exotic sources of photons before/during recombination.



So this provides us with a constraint on the dark matter parameter space.

*We can now use **scattering** as a second constraint, further shaving down the available parameter space of these types of models....*

Scattering Kinematics for $\chi_j N \to \chi_k N$

$$\Delta m \equiv m_k - m_j$$

$\Delta m > 0$ ➡ **"Upscattering"**
Typical case studied in *inelastic* DM scenarios. DM scatters off nucleus into higher mass "excited" state.

$\Delta m < 0$ ➡ **"Downscattering"**
DM scatters off nucleus into lower mass state. Δm released as kinetic energy

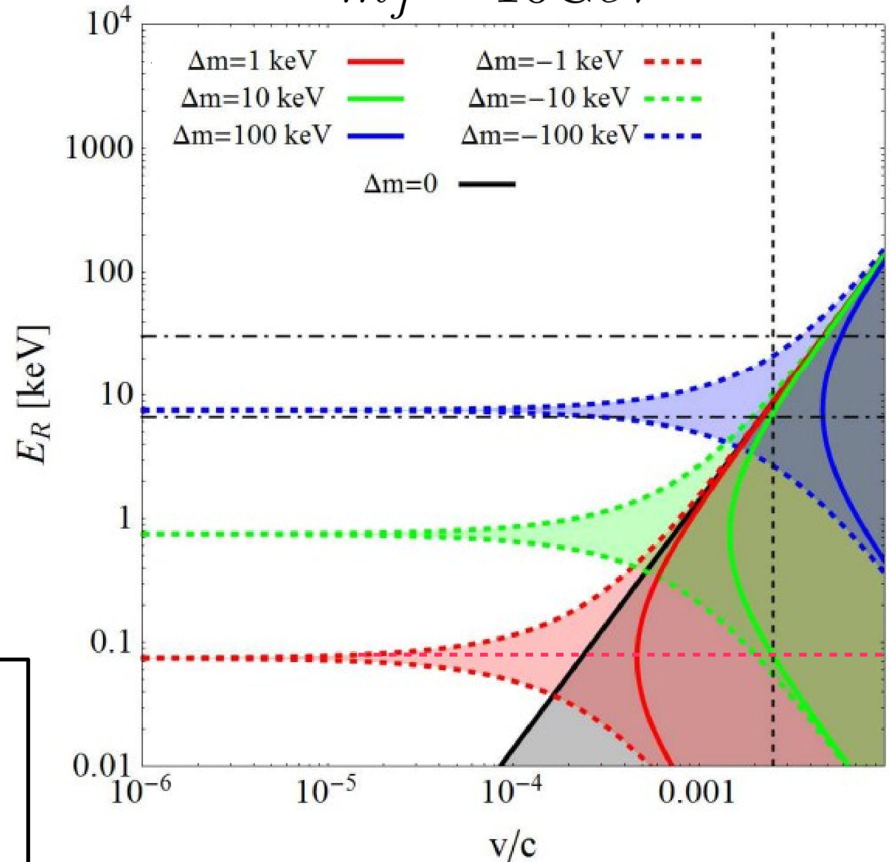
For $\Delta m \ll \{m_i, m_j\}$,

$$\boxed{E_R \approx \frac{\mu_{Nj}^2 v^2}{m_N}\left[1 - \frac{\Delta m}{\mu_{Nj} v^2} + \left(1 - \frac{2\Delta m}{\mu_{Nj} v^2}\right)^{1/2} \cos\theta\right]}$$

where, $\mu_{Nj} = m_N m_j/(m_N + m_j)$

Range of E_R at XENON100

$m_j = 10\mathrm{GeV}$



Recoil Energy Spectra

- ***Down/upscattering lead to unique and distinguishable recoil energy spectra***
  (which is our only observable at current direct detection experiments)

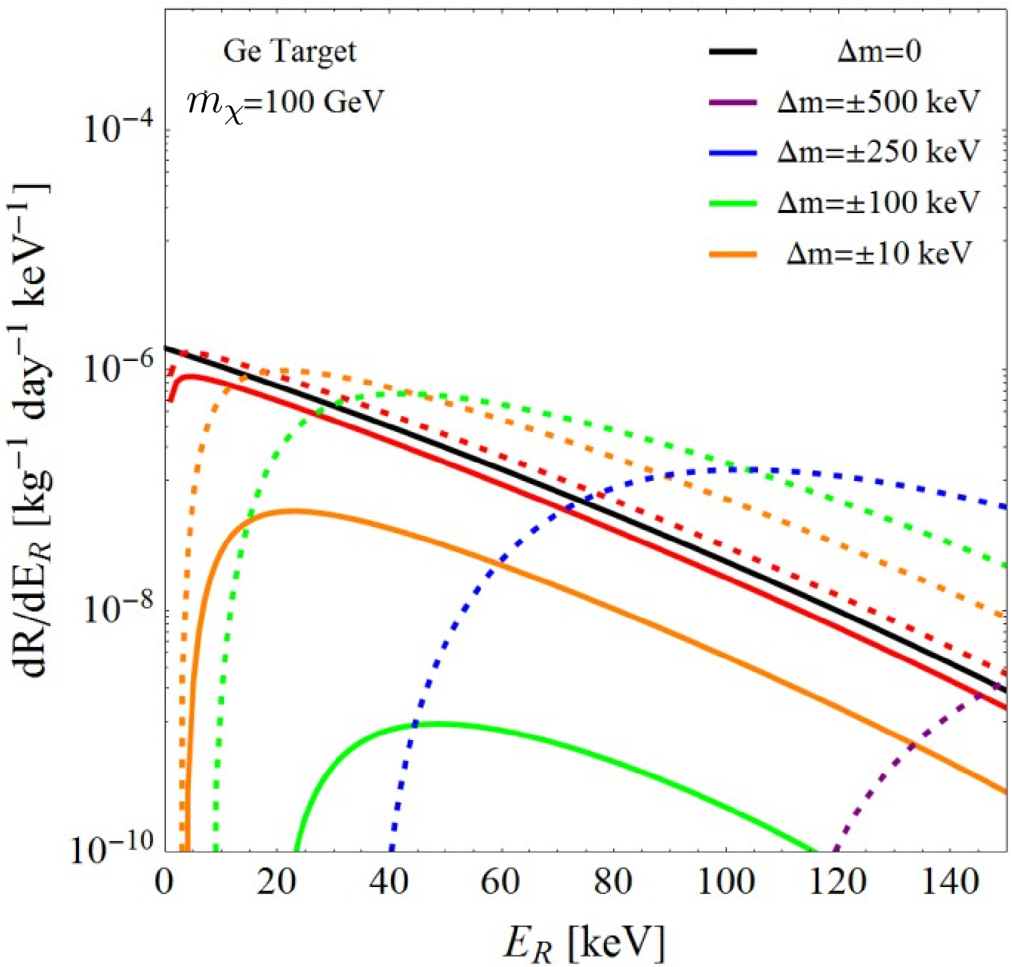
- ***Downscattering generally more accessible to direct detection***
  (due to energy released from Δm)

- ***Upscattering becomes undetectable for high*** Δm
  (though bounds from decays become better)

Here, we have chosen $c_{\pm}$ *such that*

$$\sigma_{n0}^{(SI)} = 10^{-46}\ \mathrm{cm}^{-2}$$

Upscattering (solid)
Downscattering (Dashed)



These spectra would be a *smoking gun* signal for multi-component dark matter.

Now combine constraints from scattering and decay

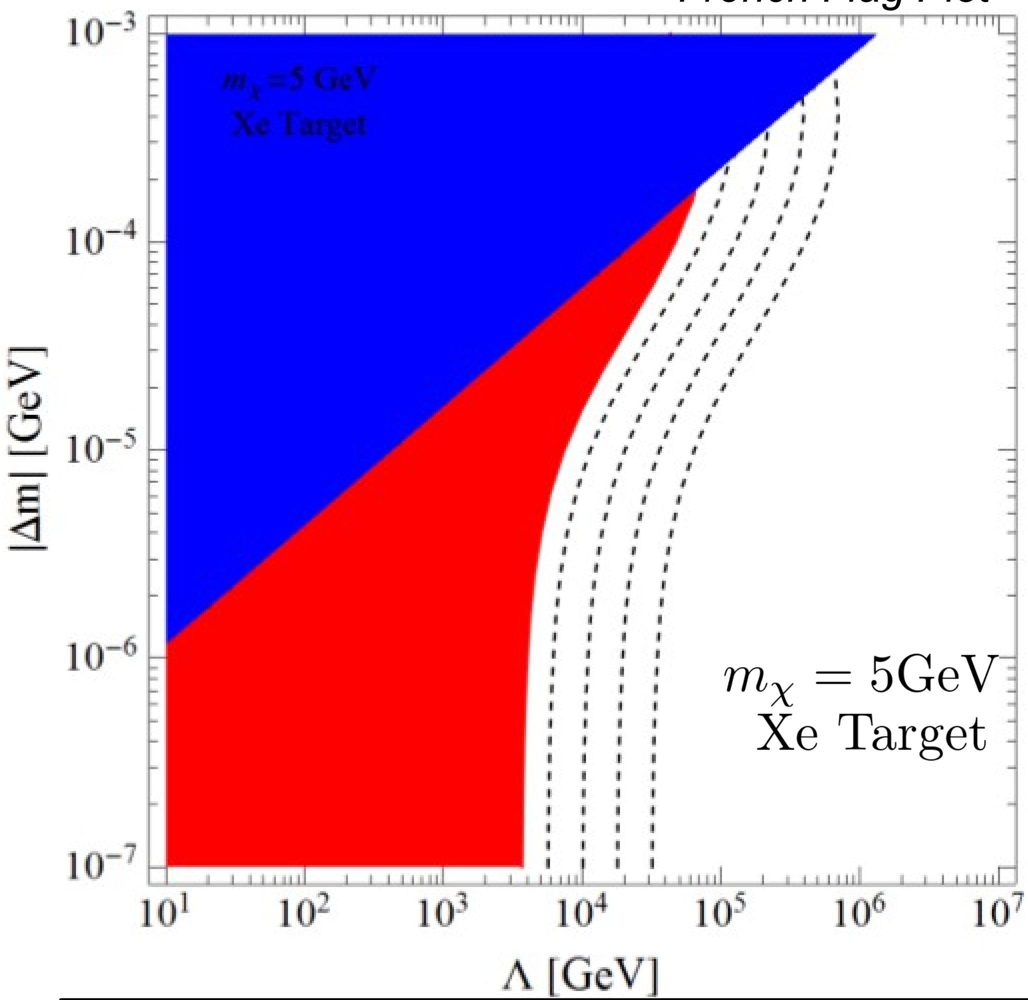
Excluded by XENON100

- **Most recent limits** from [arXiv:1207.5988].
- Total event rate for nuclear recoils with $6.6\ \mathrm{keV} \leq E_R \leq 30.6\ \mathrm{keV}$
- Most recent limits restrict DM to interact at a rate $R \lesssim 5.66 \times 10^{-4}\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1}$.

Excluded by astrophysical (CMB) constraints on decays to photons

- **Largely model independent**... follow directly from existence of operators allowing downscattering.
- **Region does not include current/future Planck data,** which may eat further into parameter space
- **Region does not include other operators** (e.g., tensor), which may have substantially more stringent bounds.

"French Flag Plot"



- Scalar operator: $\mathcal{O}^s = \dfrac{c^{(s)}}{\Lambda^2}(\overline{\chi}_i\chi_j)(\overline{q}q)$
- Dashed lines represent event direct detection event rate of $R = \{10^{-4},\ 10^{-5},\ 10^{-6},\ 10^{-7}\}\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1}$

Conclusions

- Multicomponent dark matter models are **well motivated** theoretically and experimentally.
- This scenario naturally leads to the possibility of DM decay.
- Decay is characterized by the **same operators** as those governing scattering rates.
- These models open up the possibility of *upscattering* and *downscattering*, which lead to **unique recoil energy spectra**.

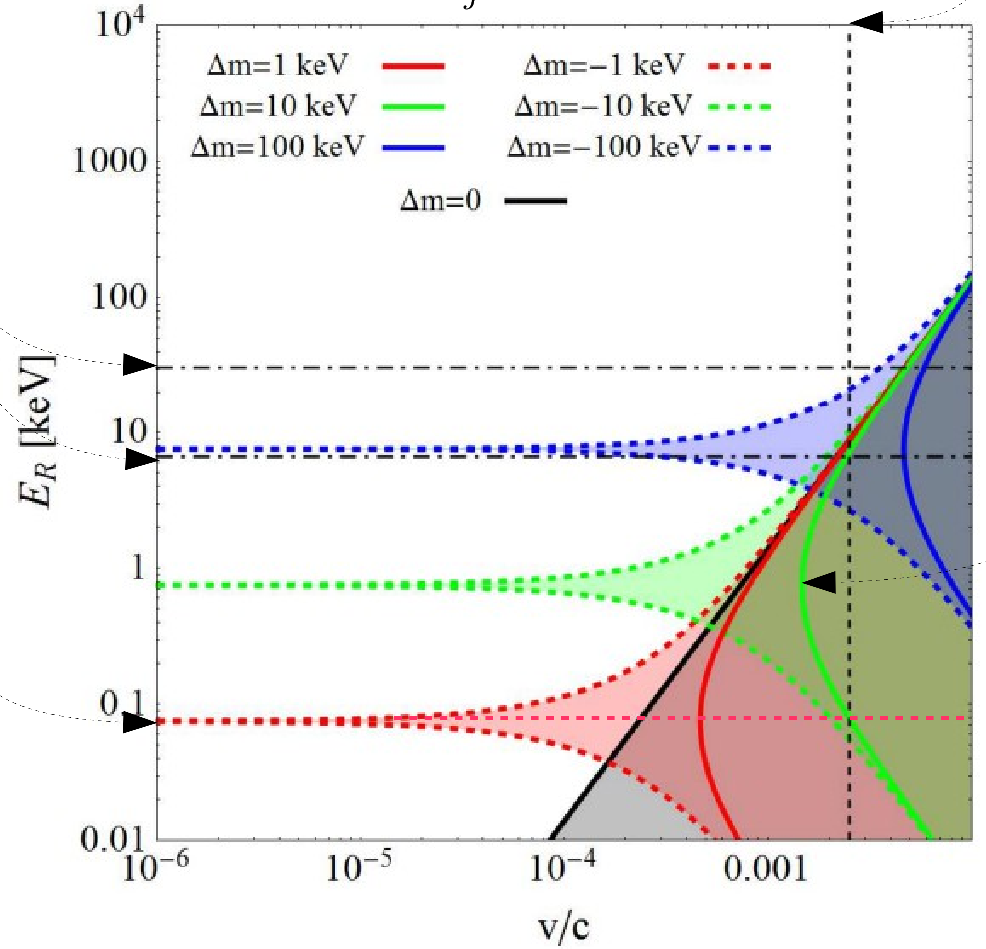
The interplay between direct detection experiments and DM decay provide a novel constraint on dark matter parameter space.

Thanks for coming!

Backup Slides

Range of E_R at XENON100

$m_j = 10\mathrm{GeV}$



- Expected velocity cutoff v_{esc}
- Min/max recoil energies used by XENON100 analysis
- Energy threshold for upscattering: $v > \sqrt{m/\mu_{Nj}}$
- "Stationary" particles: Energy Δm given to χ_k and N

$$E_R = \frac{-\mu_{Nk}\Delta m}{m_N}$$

- Scattering assumed isotropic in CM frame

$$E_R \approx \frac{\mu_{Nj}^2 v^2}{m_N}\left[1 - \frac{\Delta m}{\mu_{Nj} v^2} + \left(1 - \frac{2\Delta m}{\mu_{Nj} v^2}\right)^{1/2} \cos\theta\right]$$

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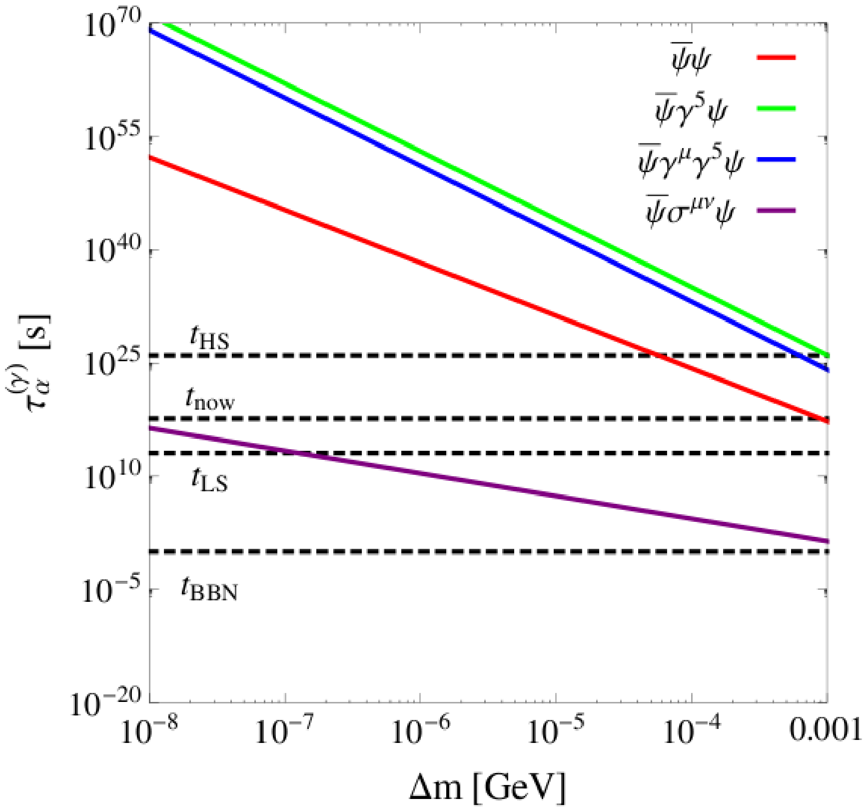
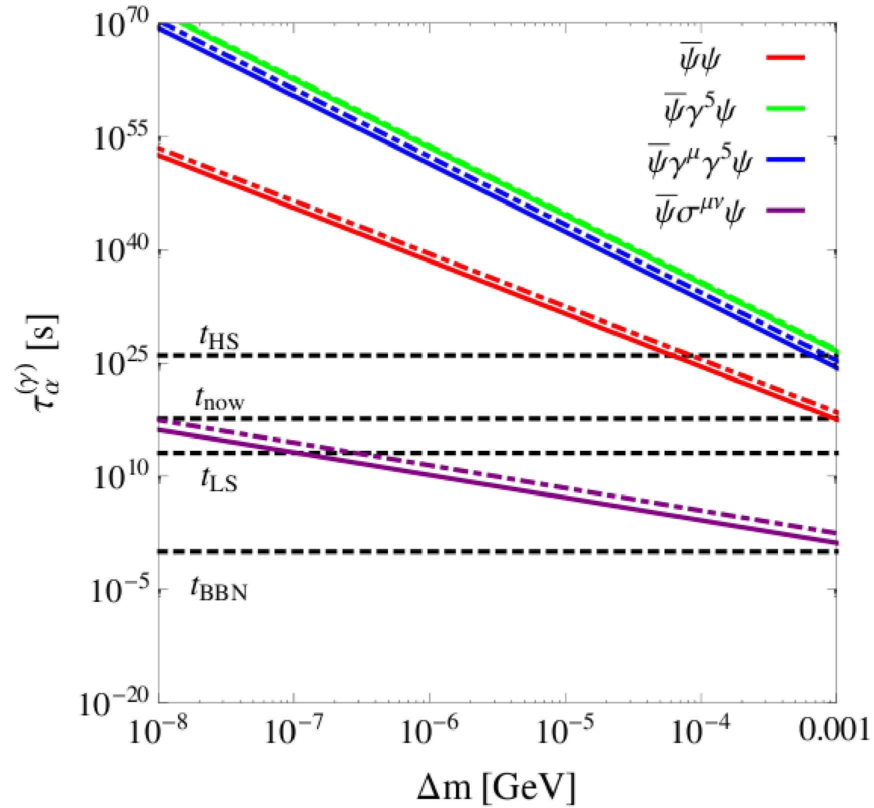


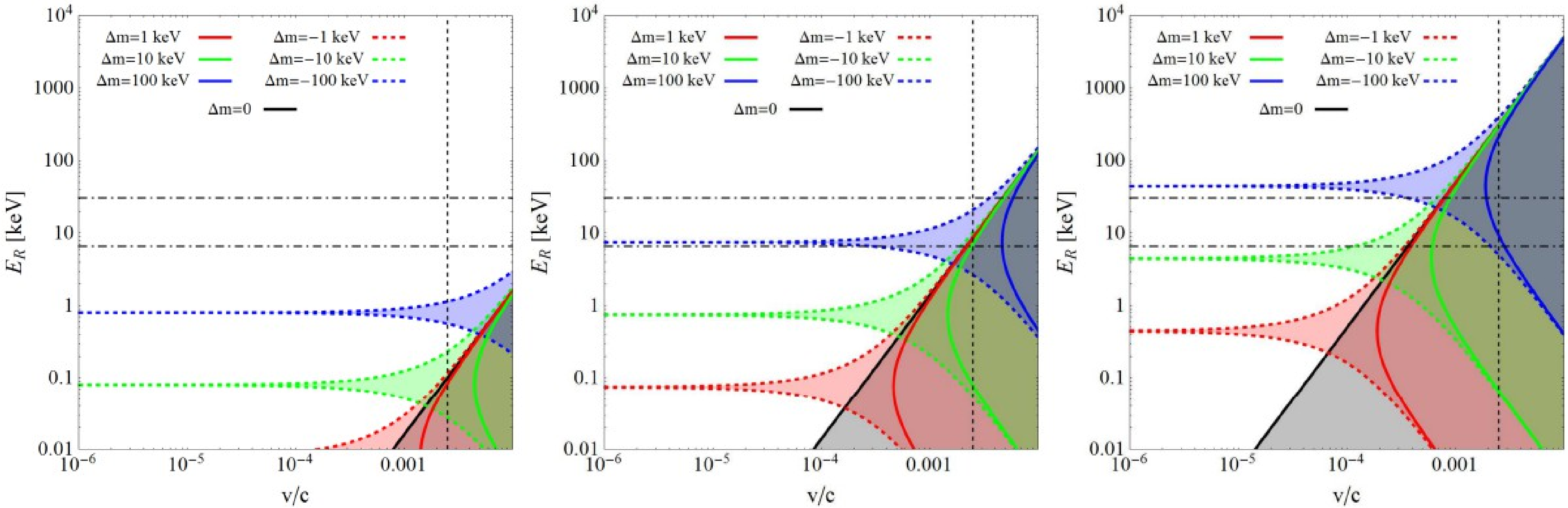
$$c_+^{(\alpha)} = 1, c_-^{(\alpha)} = 0 \quad \text{(solid)}$$
$$c_+^{(\alpha)} = 0, c_-^{(\alpha)} = 1 \quad \text{(dashed)}$$



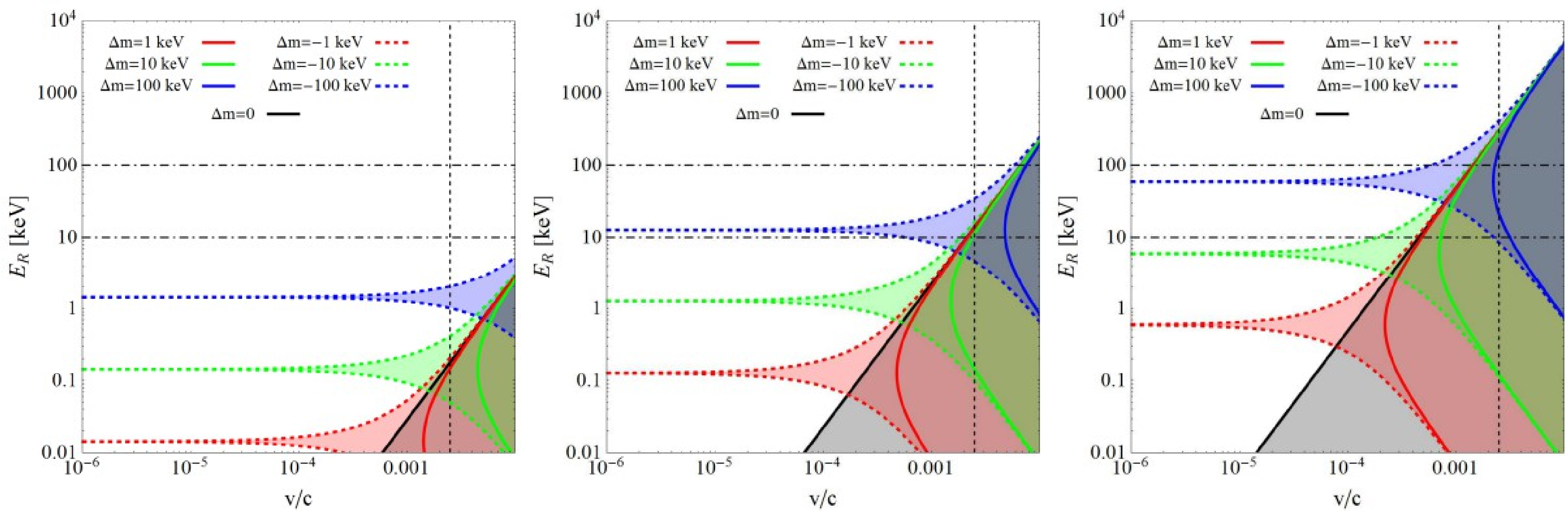
Lifetime of dark fermion which decays via $\chi_j \to \chi_i \gamma$ and $\chi_j \to \chi_i \gamma\gamma$

$\Lambda = 10$ TeV $\qquad m_i = 100$ GeV

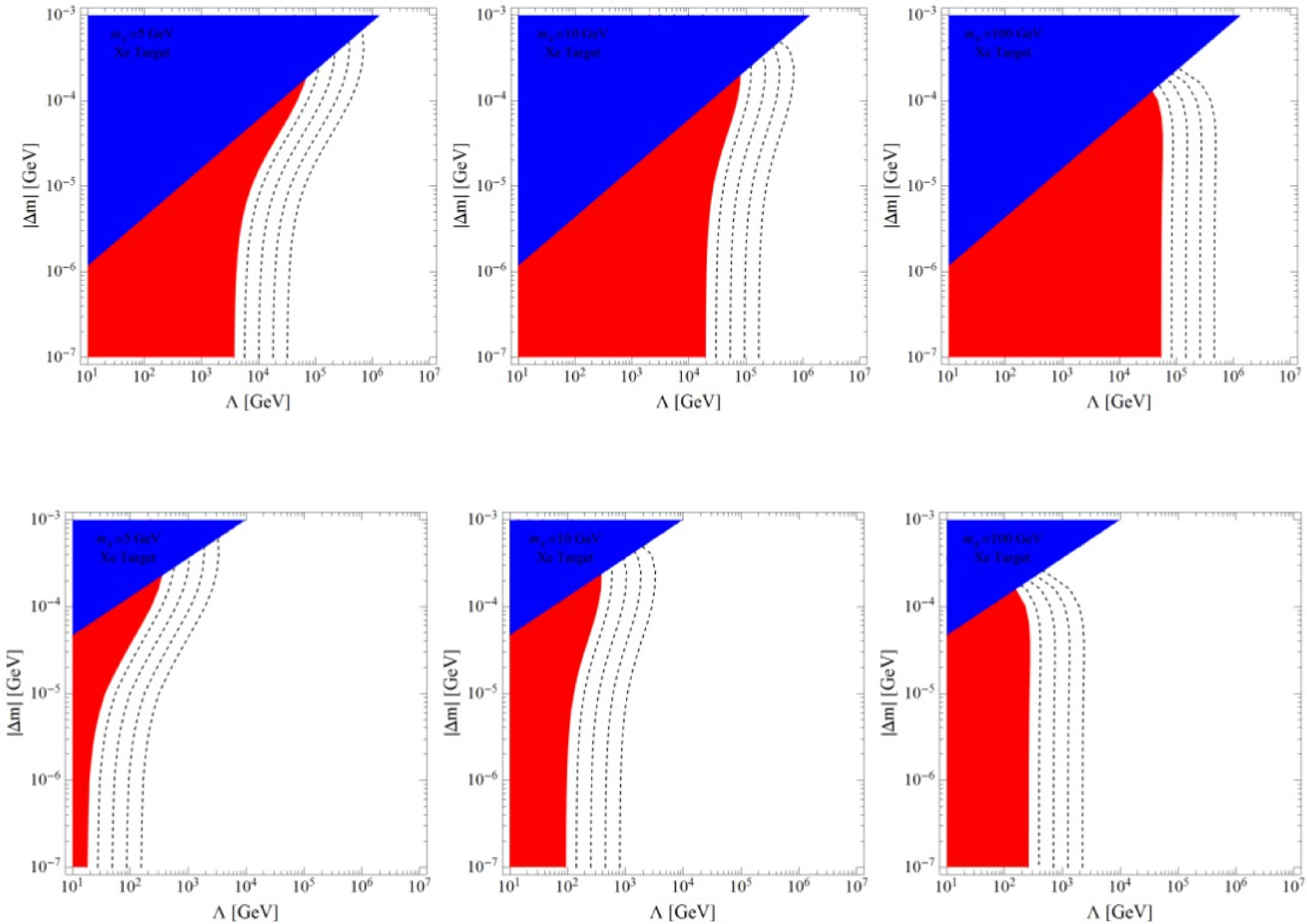
Xenon target --- XENON100



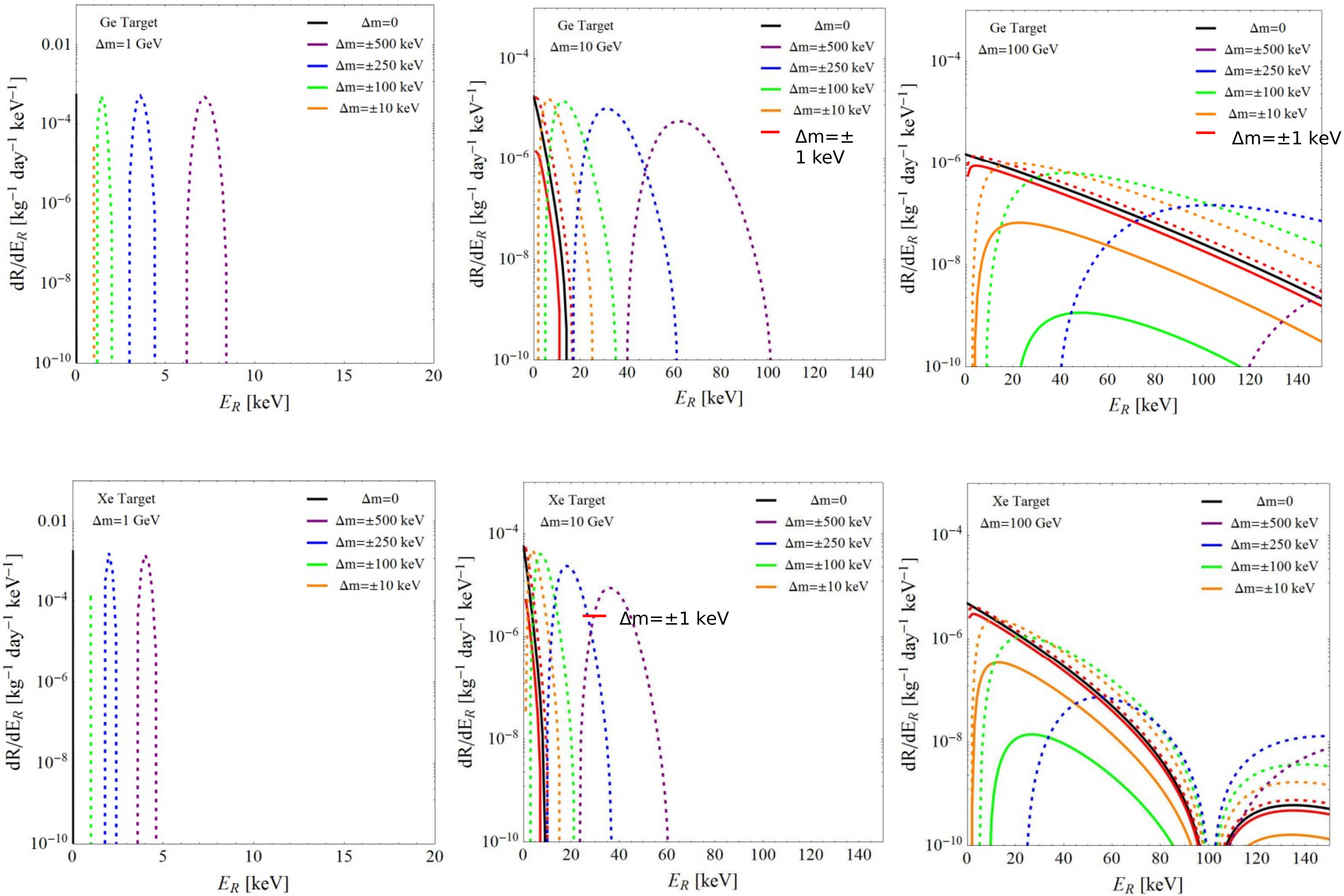
Germanium target --- CDMS II



$m_j = 1$ GeV $\quad$ $m_j = 10$ GeV $\quad$ $m_j = 100$ GeV



m_χ=5 GeV
Xe Target
m_χ=10 GeV
Xe Target
m_χ=100 GeV
Xe Target
m_χ=5 GeV
Xe Target
m_χ=10 GeV
Xe Target
m_χ=100 GeV
Xe Target
|Δm| [GeV]
Λ [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}



Ge Target
Δm=1 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Ge Target
Δm=10 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
Δm=± 1 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Ge Target
Δm=100 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
Δm=±1 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Xe Target
Δm=1 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Xe Target
Δm=10 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
Δm=±1 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Xe Target
Δm=100 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]